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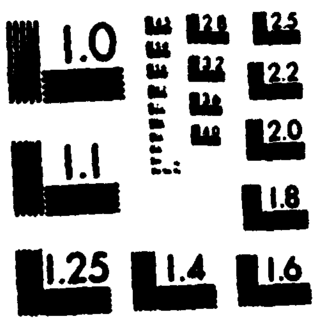

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AN EXPERIMENTAL STUDY OF TURBULENCE PRODUCTION MECHANISMS IN BOUNDARY LAYER FLOWS

By

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Final Report

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I) INTRODUCTION

The major goal of ~~our~~ this research has been to identify the mechanisms responsible for turbulence production near smooth walls. Although many dynamical features of the turbulence production process have been previously identified, and many models proposed to explain how these features came to be, the reasons for their existence, and for their evolution into turbulent eruptions are still not satisfactorily understood. Our research has succeeded in producing a unified picture of p. 2 wall region structure, by focusing attention upon the interaction which results from the passage of microscale coherent motions—which get into the buffer region from farther out in the layer—with the wall and the sublayer flow field. These microscale motions create pressure gradients near the wall, which result in the generation of new vorticity and the redistribution of existing vorticity. Both of these processes result in the creation of local concentrations of vorticity. Once a local concentration is set up it is unstable to small perturbations; thus, through self induction, and the action of the strong strain rate field on the perturbed region of fluid, very rapid dynamical effects are observed. The result of the interactions is a local feature in the wall region, which we call a pocket. Most of the production of turbulence in the wall region appears to be associated with the formation and evolution of the fluid within these pocket flow modules. We have determined that there is a very high correlation between the formation of a pocket and the presence of the microscale vortices immediately above the wall. Although the pockets are repetitive features, easily identifiable in the visualized sublayer by their shapes, their detailed evolution varies considerably depending upon the orientation and strength of the microscale motions that interact with the wall and sublayer.

We have also speculated upon the causal mechanisms beyond the concept of a perturbation that results in a local pressure gradient, to the type of flow field that could produce the local pressure gradient, but verification of the causal mechanisms will require significant additional work.

Our research was initiated as a result of a previous reexamination of the wall region of a turbulent boundary layer which indicated that the central structural feature of the turbulence production process was completely overlooked by previous investigators. We initially decided to study the underside of a turbulent spot, but quickly discovered that the rate of production is so rapid under a spot that isolation and documentation of the central structural feature was more difficult to accomplish than in the fully turbulent boundary layer, which we then focused the majority of our attention upon.

We feel that a lot has been accomplished so far. As it has turned out the facts have forced us to almost start from "scratch" rather than build upon the work of others. This has meant rather slow (but steady) acceptance by the rest of the community as they begin to do overlapping experiments (an example is an article to be published by Murlis, Tsai and Bradshaw in the *Journal of Fluid Mechanics*, the abstract of which is included in Appendix A).

A brief chronological review enumerating of the major steps in our research program is presented below. This is followed by the scope of each of these phases, then by a review of the major results. Publications generated during the course of this work are indicated in the references by an asterisk.

II) MAJOR GOALS OF OUR RESEARCH

1) Having established the existence of a local flow module which was not observed by earlier investigators, but which appeared to be the precursor of the streaky structure and the bursting process, an experimental program was established to determine its importance. The first step was to determine whether the flow modules were a universally observed wall region phenomenon, or only a feature of low Reynolds number turbulent boundary layer flows.

2) Having witnessed them in all wall bounded flows—taking care to use different experimental techniques to do it—we performed experiments in fully turbulent boundary layers to determine the length scales and frequency of occurrence of the features which we then called "pockets". Next we began to study the flow fields associated with the pockets. Since each pocket evolved rapidly, flow fields could only be understood by documenting their form at specific stages in the pocket evolution (Taylor's hypotheses could not be used). The wire was at $y^+ = 15$ for this study.

3) The complexity of the pocket flow field investigation required a working model to enable sense to be made out of the unsteady, three-dimensional flow field. We discovered that the dynamical properties of vortex ring/wall interactions had many of the evolutionary features of the pocket flow module. Furthermore, vortex ring-like eddies also appeared in actual boundary layer visualizations; thus a study was begun

of the flow fields which evolved as a result of this interaction.

4) Having established a preliminary flow field picture throughout the pocket evolution, with the help of the vortex ring wall interaction information, attention was shifted to the flow field(s) responsible for the creation of the pockets.

5) Because of the great similarity found between the pocket formation and the pattern vortex rings created on a wall, we began to search for the existence of vortices above the wall in the turbulent boundary layer.

6) Having indeed found that naturally occurring vortex rings created pockets in boundary layers, we witnessed a more general phenomenon. It became clear that the major interaction that the rings were having with the wall was to create a local favorable pressure gradient, which was accompanied by a local adverse gradient at the boundaries of the interaction. These were of sufficient magnitude to create new vorticity and redistribute the new and existing sublayer vorticity into concentrated layers or into vortices. Other motions, of the scale of the vortices, were observed to move toward the wall and also create pockets. These appeared to be induced by vortices which existed farther away from the wall. Thus we have begun to re-examine our data for signs that non-vertical sweeps result in the same pockets as vertical sweeps do. It is also important to note that not all vortices which passed over the wall resulted in the formation of a pocket. In particular, the hairpin-like vortices that are observed to form at the downstream boundary of a pocket

which formed upstream of our probe and then convected over it, often have little effect on the visualized sublayer or at the probe if it is located below the hairpin.

7) The vortices emanating from the pockets have been studied at y^+ = 18.9 and 24.2. At 18.9 they have significant vorticity, but don't have large Reynolds stress values. However, at y^+ = 24.2 the vorticity has rolled up into a vortex and significant Reynolds stress is associated with the outward moving hairpin.

III) SCOPE OF THE PROJECTS INVESTIGATED

1) The following flows were investigated to determine the existence of the pocket flow modules in wall bounded flows:

a) Fully developed turbulent boundary layer over the R_θ range 679 to 3907;

b) The interaction region between a turbulent spot and a laminar boundary layer over the range $R_x \approx 10^5$ to $4x10^5$;

c) Flow under turbulent spots for $R_x \approx 10^6$;

d) Transition of a laminar boundary layer due to turbulent shear layer interaction;

e) Fully developed turbulent channel flow for R_D = 10,000 - 23,000;

The vortex ring/wall interactions and channel flows were only investigated by visual means.

The importance of the pocket flow modules was determined in the fully turbulent boundary case at $R_\theta = 679$ by simultaneous flow visualization in two planes and cross-stream vorticity measurements using hot-wires. Our principal objective was to determine the ensemble averaged Reynolds stress and shear associated with the features. In the other flows, evidence of the importance was gathered by noting the frequency of occurrence and their association with the ejections and streak formation. We further established the importance by determining the length scales and frequency of occurrence of the pockets in the turbulent boundary layer case, and in the turbulent wake/laminar boundary layer interaction case, and comparing them to accepted data.

2) Our study of the flow fields was done at very low Reynolds number in the fully turbulent boundary layer case. We used simultaneous flow visualization in two orthogonal planes and hot-wire anemometry using a four wire vorticity probe. The signals were digitized and stored on an LSI 11/23 computer. They were later processed to give u, v, uv, $\partial u/\partial y$, $\partial v/\partial x$, ω_z and s_{xy}, and a host of turbulence "detector" functions.

3) The model studies of vortex ring/wall interactions involved visualization studies only, although they employed two orthogonal views with at least one view in a laser sheet. They were performed on both still and moving walls in water. High speed movies were made of the interaction of wall layer fluid (dyed green) and ring fluid (dyed red).

4) For our study of the flow fields responsible for the formation of

pockets, simultaneous flow visualization and hot-wire anemometry utilizing a cross stream vorticity probe was employed. We studied a fully developed turbulent boundary layer with our probe set at $y^+ = 24.2$, and $R_\theta = 679$. The visualization involved a flood illuminated plan view and laser sheet illuminated side view. This allowed us to see the flow field patterns which existed above the wall when a pocket formed in the sublayer.

5) Because of the complexity of this task, for our first try we limited our ensembles to visual impressions of pockets and hot-wire signatures of the flow field above the pockets (aided by the poorly resolved laser sheet visualization) which could be interpreted as resulting from vortices.

6) The hypothesis that the primary interaction of the vortex induced wallward flows was to create pressure gradients which acted to rearrange the sublayer fluid into a pocket, was examined only by inference from the combined hot-wire and visual signals, and through extrapolation of the behavior of models.

7) Vortices which result from the pockets have been investigated both visually and using combined flow visualization and hot-wire anemometry at $y^+ = 18.9$ and 24.2.

IV) SUMMARY OF MAJOR RESULTS

A) NEW PHYSICS OF THE TURBULENT BOUNDARY LAYER

i) The important sublayer disturbances are initiated by the movement of outer region flow field fluid toward the wall.

Perhaps the most important result to come out of this investigation is the fact that the turbulence production process is initiated by the movement toward the wall of a local region of fluid. The length scales of these regions are not large compared to δ, and based upon measurements of their footprints, as well as of the motions themselves, appear to be approximately Taylor microscale (Falco 1977b, Falco 1979, Falco and Lovett 1982).

We have studied the form and causes of the motions that move toward the wall. The situation is complex, but the following facts have been observed:

a) Vortex ring/like eddies, oriented so that they would convect upstream and away from the wall, have been observed to create pockets. We know that they are rings and not hairpins because our vorticity probe has traversed the lower half of the eddies and measured spanwise vorticity of the opposite sign from that found in the top part of the eddy (Falco 1980, Falco and Lovett 1982, Lovett 1982, also see Falco 1977a, Signor 1982, and

Signor and Falco 1982).

b) Wallward moving motions with approximately the same length scales, that have little perturbation vorticity, have been observed to create pockets that appear generally similar to pockets formed by the vortex ring/wall interactions. These motions sometimes appear to be remnants of the large scale sweeps, but at other times appear to result from vortex induction by rings whose lower lobe is in the log region (Lovett 1982).

This information contrasts with the long-standing hypothesis that elongated streamwise vortices, which were attached to the wall, "pumped" fluid both towards and away from the wall. Furthermore, it adds significant detail to the suggestions that inner/outer region interactions resulting from the movement of fluid toward the wall are the dominant turbulence production mechanism. Most of these hypotheses have suggested that large scale motions;. i.e., motions the scale of the shear layer thickness, directly contributed to the sublayer disturbances. As we see this is not the case.

ii) Local generation and local redistribution of wall region vorticity. The microscale wallward moving fluid regions establish convected stagnation point flow fields at the wall which result in the generation of new vorticity at the wall via the relations,

$$\rho \partial u_z/\partial y = - \partial p/\partial z$$

and Eq. 3

$$\rho \partial u_x/\partial y = - \partial p/\partial x$$

An observer moving around the boundary of the intersection will see that some of this vorticity has the same sign as the mean vorticity of the boundary layer, some has opposite sign, and some appears as streamwise oriented vorticity. We feel that this is the most likely mechanism for the production of streamwise vorticity.

The incoming fluid also locally redistributes the existing sublayer fluid. This fluid, which of course has its own vorticity adds to or subtracts from the total vorticity perturbation(Falco 1979).

iii) Formation of strong sweeps in the centers of pockets

The wallward moving fluid has higher momentum than the fluid it displaces. High speed wallward moving fluid is called a "sweep". The center of the pocket patterns are regions in which strong sweeps exist. The Reynolds stress associated with these sweeps is on the average many times greater than the long time average value (Falco 1980b, 1982).

iv) Formation of streaks along the boundary of the pockets

Pressure forces which result from the wallward moving fluid drive the sublayer fluid away. Because of the finite extent of the wallward motion, an adverse pressure gradient exists at the boundaries of the interaction. Thus, sublayer fluid is driven away from the convected stagnation point by the favorable pressure gradient that exists there, and is slowed down and moves up, away from the wall, in the region of adverse pressure gradient. The result is the formation of a buildup of sublayer fluid around the interaction. This buildup is elongated in the streamwise direction because the stagnation point is convecting downstream. The result is the formation of a pair of streamwise streaks (Falco 1979, 1980b, 1980c, 1982d).

v) Formation of hairpin vortices at the downstream boundary of the pockets

Hairpin vortices were definitely detected forming at the downstream boundaries of developed pockets (Falco 1979, 1982). The word hairpin is considered appropriate because the form in which the vorticity closes upon itself right at the wall is not important with respect to the dynamics of the lifted hairpin end. These hairpins have been observed to propagate out to about $y^{+} \approx 100$. When they had formed upstream of our measuring station, and convected over our vorticity probe, we usually saw little effect. We have furthermore not observed any interaction with the sublayer fluid beneath them that led to the formation of new pockets. The evolution that ensues as these hairpins move farther out — how they breakup, or undergo an instability that results in the formation of vortex rings — requires further investigation.

vi) Staggered arrays of pockets result in very sharp $\partial u/\partial y$ signals at $y^+ = 15$

When two (or more) pockets are formed side by side, the thickening of sublayer fluid along their contiguous streamwise boundaries is the highest found. This fluid often can be followed as it is drawn into the outer layers. This has often been observed to occur as a result of vortex induction by concentrated outer layer vortices (Falco 1979).

vii) The elongated streaky structure found along the wall is not dynamically important. The longest streaks of marker are found right along the wall, and are believed to be, in part, regions that have never been rearranged by convective motions; (i.e. where nothing interesting has happened to the fluid since it passed the dye slit). Other portions are the remains of marker build up that occurs along the sides of a staggered array of pockets.

viii) The frequency of occurrence of the pockets has been measured. Pockets do not scale on outer layer parameters, which is the scaling that has been suggested by many investigators for the turbulence production process. We have found, however, that they do scale on wall region variables:

$$\bar{T} u_\tau \rho/\mu = 25$$

(Falco and Lovett to be published).

ix) The length scales of the overall streaky structure are also found to be Reynolds number dependent, and do not scale on either inner or outer layer parameters. When non-dimensionalized on inner region parameters they increase with R_θ as the .4 power (Falco and Lovett, to be published).

x) The length scales of the pockets have been measured over the range 738 < R_θ < 4000. Their scales also do not depend solely on inner region variables. This is consistent with the strong role of outer region coherent motions described above. When non-dimensionalized on inner region variables the pocket widths increase as R_θ to the 1/3 power (Falco and Lovett, to be published).

B) NEW PHYSICS OF TURBULENT SPOTS

i) Spreading into the laminar boundary layer due to pockets

Vortex ring/like typical eddies have been observed to be rotated towards the wall at the front and sides of the spot by the large scale vorticity which exists at these boundaries, and to create pockets in the laminar boundary layer. These pockets appear similar to those found in fully turbulent boundary layers (Falco 1978). They evolve into lifted streaks of low speed fluid and into hairpins which lift off and are scrambled. This all happens within a very short time scale. Its evolution of the pocket is the processes that incorporates the former laminar boundary layer fluid into the spot. This accounts for its rapid growth. Spot growth is not independent of Reynolds number; instead spots grow more slowly as the Reynolds number increases. The connection between this and the fact that pockets decrease in scale in the fully turbulent boundary layer as the Reynolds number increases is being explored (Falco, in preparation).

ii) Hairpins at upstream end

Hairpins have been observed to form at the upstream boundaries of turbulent spots, and to propagate downstream into the body of the spots. Thus, in a laser sheet streamwise plane, one would see both vortex ring/like typical eddies and the tops of hairpins.

iii) Taylor-Gortler vortices at upstream end

The motions at the upstream boundary of the spots appeared to be Taylor-Gortler vortices. In fact their breakdown at the upstream boundary of the spot, which resulted in hairpins, was completely consistent with the breakdown observed by Bippes as the Gortler number exceeded its critical value.

iv) Higher density of pockets underneath

Underneath the body of turbulent spots, we have witnessed the existence of a considerably higher density of pockets than found under a fully developed turbulent boundary layer. This results in more frequent pocket-pocket interaction and presumably higher wall shear stress than found under a turbulent boundary layer generated from the same location by a trip.

C) NEW PHYSICS OF TRANSITION DUE TO HIGH FREE STREAM TURBULENCE LEVELS

i) Pockets form in the two-dimensional laminar boundary layer

If the turbulent wake of a circular cylinder intersects a laminar boundary layer, the laminar layer becomes turbulent. The process has been examined, and found to be the result of disturbances caused by vortex ring/like eddies which intersect the layer and cause pockets to form. The pockets evolve as described above and, as a consequence, the layer becomes turbulent. This process does not involve the presence of Tollmien-Schlichting waves. On the other hand, because the laminar boundary layer is two dimensional it shows us that pockets do not form as a result of the evolution of some existing streamwise vortex structure.

D) NEW PHYSICS OF VORTEX RING/WALL INTERACTIONS

i) Onset of strong viscous forces

The evolution of a vortex ring as it comes into contact with a wall is essentially governed by strong viscous forces. Inviscid theory breaks down early in the evolution; this has the overall result of destabilizing the ring, and creating a highly turbulent mass in its place. When wall dye marker is used, the footprint of this interaction shows the same characteristics as the pockets found in the wall bounded flows discussed above.

ii) Generation of new vorticity at wall

Experiments performed with the ring moving towards the wall in a quiet ambient clearly showed that new vorticity was generated at the wall by the incoming pressure field of the vortex ring (see equation 1).

iii) Mutual interaction of ring and newly generated vorticity

While this new wall layer vorticity is being generated, the ring is still governed essentially by inviscid dynamics. Thus, it is being stretched and its vorticity amplified. The portion of the ring closest to the wall stretches the most. By induction this portion of the ring redistributes the newly created wall layer vorticity which is initially distributed over the wall into a discrete vortex. The strength of this vortex is less than that of the amplified ring vortex, which causes the wall vortex, which is of opposite sign, to wrap around the ring vortex. It is during this process that viscous diffusion takes over and the ring vorticity can no longer be considered to be a closed vortex tube. What remains appears as a hairpin, with legs anchored into the wall. Vortex stretching is no longer occurring, but the remaining wall layer vorticity which has been rearranged into a vortex, is induced away from the wall by the hairpin portions of the former ring.

iv) Rapid breakup

Shortly after the portion of the ring that was farthest from the wall induces the vorticity generated at the wall upward, the ring fluid becomes violently turbulent. The lifted wall fluid immediately follows, and a rapidly growing turbulent plume results.

An annotated movie has been made showing the stages of evolution described above, Falco (1980).

v) Evolutions with preexisting wall region vorticity

Similar experiments were performed with the ring moving toward a moving belt at a number of shallow angles. By keeping the belt at a fixed speed, a given circulation is established for the vortical layer. However, by starting the belt at different time intervals after the ring is fired we could vary the local strength of vorticity in the layer. Experiments with the ring intersecting the wall on which a thin vortex sheet existed showed a very different evolution from those in which identical strength rings approached the wall on which the layer had become thicker (again, in both cases the circulation of the wall layers were the same). In the case of the thin layer, the ring did not induce the wall layer fluid far off the wall; it was essentially absorbed into the wall layers. For the diffused layer the ring evolution looked very similar to the one described in a quiet ambient; i.e., both the ring and wall region fluid become a rapidly outward moving turbulent mass.

Since the sublayer in a turbulent boundary layer will randomly vary in strength for the approaching vortex ring/like eddies, predicting the evolution of the interaction appears to be impossible. This helps to explain the wide variety of evolutionary details found for the pockets, and the large variance in the ensemble average statistics of this evolution.

E) DEVELOPMENTS IN EXPERIMENTAL TECHNIQUE

i) Use of mutually perpendicular laser sheets

All the evolutions described above are essentially three-dimensional. To obtain quantitative three-dimensional visual information, we resorted to mutually perpendicular laser sheets. The information from both sheets and a digital clock were fit on a single movie frame using split field photographic techniques. For some experiments an illuminated "corner" formed by two intersecting laser sheets was created. A camera could be aimed at 45° to both sheets to obtain a perspective view.

ii) Use of flood illuminated sublayer slit marking and laser sheet illumination at the same time

The majority of sublayer information which exists consists of dye marked sublayers which have been flood illuminated. Therefore, to have a strong basis of comparison for our visual information we needed to use this technique while at the same time employing laser sheet visualization in the streamwise-normal plane to see what was going on above the wall when the sublayer was disturbed. Our solution was to optically filter the green light from the flood illuminated marked sublayer, and pass only the green laser light in the side view. The flow in the outer part of the boundary layer was also marked by smoke from a slit further upstream. This smoke had to be of lower intensity so that discrimination between wall and outer region fluid could be made. When used in water with fluorescent dye of different colors this technique allowed visual discrimination of ring and wall layer vorticity even as they strongly interacted.

iii) Use of hot-wire anemometry in oil fog smoke

Experiments have shown that hot-wires can be operated in the oil-fog at concentrations needed to do flow-visualization with an accuracy 3% (Burkhardt and Falco 1979, Burkhardt 1982). This is sufficiently accurate for coherent structure investigations. However, continuing efforts are needed to refine our understanding of the physics that allows this generally fortunate situation to exist, because of the more limiting requirements of drag reduction studies.

iv) Simultaneous flow visualization and hot-wire anemometry

We have refined our procedure so that one experiment involves just over one hundred set-up and calibration tasks. This requires three days for four people. As we gradually automate, further reductions are expected, but we feel the technique is rapidly approaching the stage where a graduate student with a technician's help should be able to perform meaningful simultaneous visual/hot-wire experiments.

F) DEVELOPMENTS [illegible] FOR [illegible] DATA ACQUISITION AND REDUCTION

i) Computer programs have been written which allow our home built 16 channel 12 bit A/D converter which simultaneously samples and holds up to 16 signals before multiplexing them (allowing the multi wire derivatives to be obtained) to store 11 k words and a timing signal which is also photographed. The algorithms allow data to be [illegible] at up to 30 kH$_z$ for each wire of a 4-wire vorticity probe.

ii) Complete data reduction on a micro computer

Because of the need to get large amounts of data from our data acquisition system to a computer that can reduce the data, and because we do not have the capability to transfer the data to MSU's central computer (this would require a magnetic tape drive and is not actually encouraged by the computer center), we are pursuing a goal of being able to completely reduce our data on LSI 11 micros. Over thirty data reduction algorithms, necessary for everything from converting millivolts/bit to voltages, to those necessary for plotting, have been written for the DEC system. Our experience so far has been that on the order of 90 floppy discs are required in the reduction process if ensemble averages on the order of 50 events are to be considered. This has become an overwhelming bookkeeping problem, and is a very time consuming procedure, but with the advent of additional funds to enhance our computing capabilities we expect this will be the most effective alternative.

6) COMMENTS ON TURBULENCE DETECTION TECHNIQUES

It is generally known that turbulence detection schemes do not work in the wall region, or for that matter in the outer region (Falco 1980a). In the wall region, they have led to the wrong scaling laws, and have led to results that differed from each other by more than an order of magnitude. We have used simultaneous 2 view flow visualization and our four wire cross-stream vorticity probe to determine what patterns in the wall region result in the high Reynolds stress at the wall. This is essentially the complete set of information against which to test any turbulence detection scheme. We chose to test the rather widely used scheme called VITA (Gupta, Laufer and Kaplan 1971). Results showed that VITA detected only a small fraction of the turbulence production events, and they further showed the specific stage in the evolution of the pockets that it was sensitive to (Falco 1980b). We are currently evaluating other schemes, and intend to produce one of our own that reflects the major aspects of the process.

V) CONCLUSIONS

The coherence associated with the production of turbulence near a wall is greater than anticipated before this investigation began. It is clear that many aspects of the physics can be modelled by the vortex ring/wall interaction, however, it appears that somewhat less stringent conditions can also initiate new production. Furthermore, the same physics appears to govern production for Reynolds numbers up to the onset of the law of the wake (which signals the onset of high Reynolds number asymptotic behavior). However, further investigation is required to determine which details of the interactions are necessary and which are sufficient, before attempts at logically modifying the production rate can be made.

REFERENCES AND PUBLICATIONS

An asterisk denotes a publication resulting all or in part from this work.

*Burkhardt, W. M. 1982 Effect of an oil fog upon hot-wire anemometry response. M.S. Thesis, Department of Mechanical Engineering, Michigan State University, East Lansing, MI.

*Burkhardt, W. M. and Falco, R. E. 1978 Response of hot-wire anemometry in flows visualized by an oil-fog. Bulletin Am. Phy. Soc. Series II, Vol 23, 1978, pg. 995.

Falco, R. E. 1977a Coherent motions in the outer region of turbulent boundary layers. Phy. Fluids, Vol. 20, Part II, pp. S124-S132.

Falco, R. E. 1977b A structural model of the turbulent boundary layer. Proceedings of the 14th Annual Meeting of SES.

Falco, R. E. 1978 The role of outer flow coherent motions in the production of turbulence near a wall. Coherent Structure of Turbulent Boundary Layers, ed. Smith and Abbott.

*Falco, R. E. 1979 Structural aspects of turbulence in boundary layer flows, in Turbulence in Liquids, ed. Patterson and Zakin, University of Missouri Press.

*Falco, R. E. 1980a Combined simultaneous flow visualization/hot-wire anemometry for the study of turbulent flows. J. Fluids Eng. Vol 102, pp.174-180.

*Falco, R. E. 1980b The production of turbulence near a wall. AIAA Paper No. 80-1356.

*Falco, R. E. 1980c Turbulence production near a smooth wall (Abstract). Proceeding of the 17th Annual SES Meeting, pg. 181.

*Falco, R. E. 1980d Vortex ring/wall interactions. 16 mm movie.

*Falco, R. E. 1982 A synthesis and model of wall region turbulence structure. Proc. ICHMT/IUTAM conference on the Structure of Turbulence, Heat and Mass Transfer, Hemisphere Press.

*Falco, R. E. An experimental study of Reynolds stress producing motions in the outer part of turbulent boundary layers. Part I The shape, scale, evolution and Reynolds number dependence. submitted to J. Fluid Mech. (under revision).

*Falco, R. E. Wall region structure of turbulent boundary layers. Submitted to J. Fluid Mech (under revision).

*Falco, R. E. On the internal structure, formation and spreading of turbulent spots. In preparation.

*Falco, R. E. On the evolution of a vortex ring impinging on a wall. To be submitted to Phy. Fluids.

*Falco, R. E. and Lovett, J. A. 1982 The turbulence production process near walls. To be presented at the 35th APSDFD conference.

*Falco, R. E. and Lovett, J. A. Reynolds number dependence of sublayer structure. in preparation.

*Falco, R. E. and Lovett, J. A. The scaling of sublayer disturbances associated with the production of turbulence near a wall. In preparation.

*Falco, R. E. and Lovett, J. A. The bursting period in turbulent boundary layers. In preparation.

*Falco, R. E., Signor, D. B., and Newman, G. R. An experimental study of the Reynolds stress producing motions in the outer part of turbulent boundary layers. Part II; velocity, Reynolds Stress and vorticity fields. to be submitted to J. Fluid Mech.

Gupta, A. K., Laufer, J., Kaplan, R. E. 1971 Spatial structure in the viscous sublayer. J. Fluid Mech. Vol. 50, pp. 493-512.

Kline S. J. and Falco, R. E. 1980 Summary of the AFOSR/MSU research specialist workshop on coherent structure in turbulent boundary layers. TRL Report 80-1, Department of Mechanical Engineering, MSU.

*Lovett, J. A. 1982 The flow fields responsible for the generation of turbulence near the wall in turbulent shear flows. M. S. Thesis, Department of Mechanical Engineering, Michigan State University, East Lansing, MI.

*Signor, D. B. 1982 A study of intermediate scale motions in the outer region of turbulent boundary layers. M. S. Thesis, Department of Mechanical Engineering, Michigan State University, East Lansing, MI.

*Signor, D. B. and Falco, R. E. 1982 Reynolds number scaling of coherent motions in turbulent boundary layers. To be presented at the 35th APSDFD conference.

APPENDIX A

The Structure of Turbulent Boundary Layers at Low Reynolds Numbers.

by J. Murlis*, H.M. Tsai and P. Bradshaw
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Conditionally-sampled hot-wire measurements in the range $700 < Re_\theta < 5000$ confirm the general flow picture advanced by Falco (1974, 1977: see also Smith and Abbott 1978) on the basis of smoke observations. The intermittency factor and the turbulent transport parameters (the 3rd-order structural parameters, deduced from triple-product measurements) are independent of Reynolds number: this suggests that the basic large-eddy structure (Falco's "large motion") is nearly the same at all Reynolds numbers. The shear correlation coefficient is also nearly independent of Reynolds number, but this is partly a coincidence because the ratio of u-component to v-component mean-square intensity changes quite rapidly at Reynolds numbers $Re_\theta < 2000$. The probability density function of turbulent-zone length varies in a striking fashion with Reynolds number, qualitatively supporting Falco's finding that the small scale undulations in the viscous superlayer (which he calls "typical eddies") scale on the viscous length parameter rather than on boundary layer thickness. The average turbulent zone length, deduced as an integral moment of the probability distribution, tends to a constant fraction of the boundary layer thickness at high Reynolds number, where the "typical eddies" become small compared to the size of the classical "large eddies" (Townsend 1956). However, the probability density function as a whole depends strongly on the choice of the minimum length of irrotational "zone" that is admitted as real, L_{min}, say, so that the only general method of presenting zone-length information is as probability distributions of zone length L conditional upon L_{min}, ($P(L|L_{min})$ in the usual notation. The determination of intermittency from velocity or temperature fluctuations is

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discussed in detail because of the prevalence of erroneous or misleading results in the literature. The law-of-the-wall relations, specifically the constants in the logarithmic profile, seem to be independent of Reynolds number while, as originally deduced by Coles (1962), the defect-law profile varies with Reynolds number.

1. Introduction

The usual analysis for the velocity defect in a turbulent boundary layer in zero pressure gradient, given, for instance, by Townsend (1956), leads to the expression

$$\frac{U_e - U}{U_\tau} = f\left(\frac{y}{\delta}\right) \qquad (1)$$

where u_τ is the friction velocity $\sqrt{(\tau_w/\rho)}$. The analysis assumes that the apparent effect of the parameter $u_\tau/U_e = \sqrt{(c_f/2)}$, or equivalently $d\tau_w/dx$, is negligible. It is possible that the effect of c_f is responsible for the slight Reynolds-number dependence of equation 1 at high Reynolds number, especially in supersonic flow, discussed by Mabey (1977). However, Coles (1962) found comparatively large changes in turbulent boundary layers in zero pressure gradient at momentum-thickness Reynolds numbers $u_e\theta/\nu$ of less than about 5000, and it has generally been assumed that this is a direct effect of Reynolds number itself rather than an effect of c_f; that is, it is an effect of viscosity on the turbulence structure outside the viscous sublayer (the defect law analysis assumes viscous effects to be confined to the sublayer $u_\tau y/\nu < 30$, say: see figure 1). Huffman and Bradshaw (1972) showed that the velocity-defect profile in pipe flow is apparently independent of Reynolds number, even in the low-Reynolds-number range, and the simplest hypothesis to explain this difference between boundary-layer and pipe flow is to suppose that the Reynolds-number effects on the defect law are associated with the "viscous <u>super</u>layer", that is, the region

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